Damage assessment and survival estimates in the wedge clam (*Donax trunculus*) caught by mechanical dredging in the northern Alboran Sea

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Abstract

This paper describes the impact of dredging on populations of the wedge clam (*Donax trunculus*) at two sites along the northern Alboran coast. Damage was assessed by quantifying shell and foot damage on commercial clams caught with mechanical dredges. Survival experiments were carried out to assess their survival capacity after 24 h purification treatment and 72 h cold storage, which represents an issue of great interest for fisheries research, management and marketing. Overall, 2.4% of wedge clams suffered any type of damage, including chipped edges and scratched valves. Higher proportions of shell-damaged individuals were positively correlated to bottom features (e.g. gravel content in sediment). Moreover, higher towing speed significantly increased shell damage. Analyses of shell damage areas revealed that the anterior dorsal and ventral parts of the shell are the most vulnerable to dredging. A total of 15.9% of individuals showed damage on the foot, which seems not to affect their survival. The incidence of foot damage was mostly linked to sublethal predation, reflected in a positive correlation between the proportion of foot-damaged individuals and biomass of decapod crustaceans in the fishing ground. Finally, *D. trunculus* exhibited very low mortality rates after 24 h purification treatment (0.2-0.4%) and 72 h cold storage (0.3-3.2%). The survival rate at the end of the experiment was high (>96 %), with the highest mortality observed 96 h after the fishing day. No correlations were found between mortality rates and bottom type or towing speed.

Keywords: artisanal bivalve fishery, clams, fishing gear impact, survival rate, shell damage, foot damage

Acknowledgements

We would like to thank the skippers and crew of the artisanal fishing vessels *El Lele* (Caleta de Vélez) and *Nuevo Hermanos Madueño* (Fuengirola) for their collaboration; and to José Manuel Escobedo and the staff of the *Escobedo-Mariscos Vivos* purification and expedition centre in Fuengirola for the help provided, making the facilities available to the FEMP team. This study was developed under the collaboration agreement between *Junta de Andalucía* (Spain) and

Instituto Español de Oceanografía, within the framework of the research project entitled *Análisis y seguimiento de los recursos y actividades pesqueras dirigidas a* Callista chione *("concha fina"),* Acanthocardia tuberculata *("corruco"),* Chamelea gallina *("chirla") y* Donax trunculus *("coquina") en la costa mediterránea de Andalucía* (FEMP_AND-01). This project was funded by the European Maritime and Fisheries Fund (EMFF).

Introduction

Artisanal fisheries are a primordial and very diverse activity worldwide in terms of target species, gears and fishing strategies, representing approximately 45% of the world's fisheries, comprising 90% of all fishing jobs worldwide and nearly a quarter of the world catch (FAO-FIGIS, 2017). Within the Mediterranean Sea, artisanal fishing is of high socio-economic importance and has a long tradition (Papaconstantinou and Farrugio, 2000; Stergiou et al., 2006), being recorded as far back as in the classical works of Greek antiquity (e.g. bivalve molluscs: Voultsiadou et al., 2010). Regarding the Spanish Mediterranean, the artisanal fishing fleet comprises ca. 1500 small vessels using different gears and playing an important role in the European fishing industry (Morales-Nin et al., 2010; https://www.mapa.gob.es/es). One of the main fishing gears operated by the artisanal fleet is the mechanical dredge (hereafter MDs) to catch bivalves, which represents more than 60% of the artisanal fleet in the southeastern Spain (northern margin of the Alboran Sea) (Baro et al., 2021). This artisanal fishery is performed by small vessels on soft bottoms at depths <25 m, operating up to 6 dredges that scrape the surface of the seabed and/or penetrate the substratum using a toothed bar to dig organisms out of the sediment (up to 40-50 cm in depth). MDs are designed species-specifically but are very similar in general terms, comprising a metallic frame, a toothed lower bar whose length varies depending on the target species maximum burrowing depth, and a collecting system to retain the catch.

Wedge clams (*Donax* spp.) are among the main target molluscs in Mediterranean waters, annual landings increasing from 195 t in 2011 to 723 t in 2017 (FAO-FIGIS, 2017). *Donax* clams are suspension-feeders on phytoplankton and particulate organic matter, representing an important faunal component of the shallow soft bottoms in exposed sandy beaches (Ansell, 1983). Five *Donax* species inhabit the Alboran Sea, namely *D. semistriatus* Poli, 1795, *D. trunculus* Linnaeus, 1758, *D. variegatus* (Gmelin, 1791), *D. venustus* Poli, 1795 and *D. vittatus* (da Costa, 1778) (Gofas et al., 2011), of which *D. trunculus* is commercially exploited in the northern margin by the artisanal fleet operating MDs (Baro et al., 2021). This species is widely distributed along the Mediterranean Sea, Black Sea and Atlantic Ocean from France to Senegal (Tebble, 1966; Bayed and Guillou, 1985), inhabiting shallow (0-6 m depth) fine sand bottoms exposed to intense wave action and sediment instability (Picard, 1965). In certain geographic areas, populations of *D. trunculus* present depth segregation between size classes, with predominance of adults at greater depths down to their bathymetric limit and of juveniles on shallower bottoms (Ansell, 1983; Guillou and Bayed, 1991; Gaspar et al., 2002).

The high commercial importance of *D. trunculus* throughout European coasts has made it intensively studied for fisheries management (Baldaccini and Bianucci, 1984; Fischer et al., 1987; Pereira, 2013), parasitism and predation (Ramón et al., 1999; Salas et al., 2001; Pérez-Miguel et al., 2019), population dynamics and production parameters (Bayed and Guillou, 1985; Mazé and Laborda, 1988; Neuberger-Cywiak et al., 1990; Ramón et al., 1995; Zeichen et al., 2002; Delgado et al., 2017), and growth and reproduction (Bayed, 1990; Tirado and Salas, 1998; Gaspar et al., 1999; Deval, 2009; Tirado et al., 2011; Delgado and Silva, 2018). Nevertheless, information regarding the damage inflicted by fishing gears on this species, as well as its survival rate after being captured is still very limited (Gaspar and Monteiro, 1998; Leitão et al., 2014; Anjos et al., 2018). In this line, few studies have been carried out in the last decades to assess the impact of dredges on target species from shallow bottoms, including the smooth clam *Callista chione* (Linnaeus, 1758) caught with MDs along the southwestern coast of Portugal (Vasconcelos et al., 2011), and the striped venus clam *Chamelea gallina* (Linnaeus, 1758) caught with hydraulic dredges in the northern Adriatic Sea (Moschino et al., 2003). This information is important for the sustainability of particular fishing activities in a certain area, as they depend on the maintenance of populations of commercial species in the fishing grounds, especially considering that MDs have a direct impact on the ecosystem, affecting macrobenthic communities through mortality and injuries to surface-living and shallowly-buried fauna (Gaspar et al., 2003; Gaspar and Chícharo, 2007; Leitão et al., 2009, 2014; Urra et al., 2017, 2019; Anjos et al., 2018).

In this study, we try to answer some doubts expressed by fishermen in work meetings about their fishing activity targeting the wedge clam *D. trunculus* by mechanical dredging in the northern Alboran Sea, such as (1) the influence of the bottom type on the potential damage on shells of wedge clams during towing; (2) the cause of foot damage observed in numerous wedge clams and its potential effect on the survival rate of captured individuals; and (3) the potential effect that the purification might have on the survival of wedge clams. The purification treatment is a mandatory for commercial bivalves for human consumption that are collected in Class B areas, according to the Regulation (EC) No 854/2004. Class B areas are those from which live bivalves may be collected, but only placed on the market for human consumption after treatment in a purification centre or after relaying so as to meet the health standards referred to in the Regulation (EC) No 853/2004. The present information will help fishermen, researchers and managers to understand some aspects of the target species biology (resistance to dredges and survival rates), feeding ecology of the local benthic community (potential predators that feed on its foot), and to the type of bottom (nature of the sediments and its relationship with shell damage).

Materials and Methods

Study area

This study was carried out at two very important fishing grounds for the artisanal fleet, Fuengirola and Caleta de Vélez (hereafter Caleta), located 29.7 nautical miles apart along the littoral of Málaga province (northern margin of the Alboran Sea) (Figure 1, Table 1). The Alboran Sea represents a transition area between two basins with distinct hydrological characteristics such as the Atlantic Ocean and the Mediterranean Sea (Vargas-Yáñez et al., 2019), and highlights as a biodiversity hot-spot within European waters, with a confluence of species with different affinities (García Raso et al., 2010, Templado, 2011, Rueda et al., accepted). It is also remarkable its high productivity and habitat heterogeneity, supports many species with ecological and/or commercial importance, including the existence of spawning grounds for commercially-exploited species (Robles, 2010; Moya-Urbano et al., 2019; Ventero et al., 2021). This diversity of resources has promoted a great fishing activity in the Alboran Sea, being the artisanal fishery very well represented in the northern margin of the basin (Baro et al., 2021).

The studied soft bottoms are located inside the small bays of Fuengirola and Caleta, being composed mainly by fine sands in Fuengirola, and by fine and medium sands in Caleta, with different mud and organic matter contents (Sanz et al., 2007; Urra et al., 2011), resulting in different facies of the well sorted fine sand community.

Sampling surveys and data collection

The fishing fleet based in the port of Fuengirola consists of 52 vessels, from which 65% operates with “minor gears” (i.e. small-scale fisheries), most of them using MDs targeting bivalves, but that can direct their fishing effort towards other target species (e.g. cephalopods) in response to varying market needs and specific regulations (e.g. time-area closure to protect spawn). One of the main target species is the wedge clam *D. trunculus*, with 8909.4 kg landings (total value: ca. 90000 €) declared by the shellfish artisanal fleet in 2019 (source: *Consejería de Agricultura, Pesca y Desarrollo Rural* of *Junta de Andalucía*). On the other hand, the fishing fleet based in Caleta consists of 80 vessels, with 50 % using MDs, which declared 4934.6 kg of wedge clam (ca. 70000 €) in 2019 (source: *Consejería de Agricultura, Pesca y Desarrollo Rural* of *Junta de Andalucía*).

The damage of MDs on wedge clams and the survival rates of individuals were assessed in samples collected onboard two commercial vessels with similar characteristics. Fishing tows were performed in November and December 2018 on fishing grounds off Fuengirola and Caleta. In this fishery, once the vessel reaches the fishing ground, the anchor is cast astern and the vessel navigates freeing the cable that connects the anchor to the winch. After releasing ca. 200 m of cable, the vessel stops and MDs are released afore and set on the seabed. Then, the winch is activated to collect the anchor cable, allowing the vessel to move towards the anchor as MDs are towed at very low speed (0.3-0.5 knots, the usual working speed of the winch) for ca. 20 minutes catching specimens along the transect. MDs are hauled one by one once the anchor cable has been collected. In the present study, MDs were towed at three different speeds: lower (0.1 knots), standard (0.3 knots) and faster speed (0.5 knots). A total of 36 tows (2 sites × 6 tows × 3 towing speeds) were performed following the usual operating procedures of fishermen. Additionally, three sediment samples per fishing ground were collected using a blind semicircular-toothed dredge for further granulometric analyses, in order to characterize the sediment grain size distribution.

After each tow, all commercial wedge clams (marketable individuals with shell length ≥25 mm) were selected onboard, put into plastic mesh shellfish bags, and placed in a 50 l container with a continuous flow of fresh seawater to maintain water temperature and avoid oxygen depletion. Once in the harbour, containers with wedge clams were transported to the laboratory for further procedures.

Shell damages

The damage incidence on every collected commercially-sized wedge clam (n= 10839 ind.) was evaluated in relation to the granulometric characteristics of the seabed and to the towing speed of the fishing vessel. Damage was assessed by detecting wedge clams with chipped edges, scratched valves and crushed shells. Additionally, the position of the damage caused by dredge impact was assigned on the valves of 132 randomly selected individuals from the total of individuals observed with any type of damage (51% of 259 damaged individuals), after subdividing the valves into four areas according to the shell's main axes: anterior dorsal (AD), posterior dorsal (PD), anterior ventral (AV), and posterior ventral (PV) (based on a similar study on the smooth clam *Callista chione* by Vasconcelos et al., 2011). Subsequently, the frequency distribution of each damaged area detected in right and left valves was calculated.

In addition, a total of 2155 commercial wedge clams (ca. 360 individuals per towing speed and location) were dissected and checked for foot damage. The incidence of foot damage was assessed on a three-level scale: (i) type 0 - no damage; (ii) type 1-intermediate damage, individuals with half or less of the foot nipped or with small cuts; and (iii) type 2-severe damage, individuals with more than half of the foot nipped or with deep cuts.

Survival rates

In the laboratory, marketable wedge clams were checked for individuals with open, fragmented and/or dislodged valves and for those that did not respond to mechanical stimuli. The criteria used to determine whether an individual was alive followed that proposed by Gaspar and Monteiro (1998): an individual was considered dead or moribund if its valves gaped persistently after repeated tapping. After this first evaluation, every sample was transported inside a portable fridge to the purification center (located at 100 m from the laboratory). Wedge clams from each sample were placed in different trays with suitable open mesh sides to allow water flow and kept inside a 2000 l purification tank with a renewing seawater system for 24 hours (seawater temperature: 13 °C; oxygen saturation: 94 %). After this treatment, wedge clams were transported to the laboratory and checked for dead individuals. Then, plastic mesh bags (2 sites × 3 towing speeds × 6-8 bags) with 500 g of commercial wedge clams were stored in a refrigerator at 4 °C and checked daily for dead individuals during three days looking.

Discard analysis

The characterization of the discards generated by mechanical dredging was carried out in order to identify the main macro-benthic and demersal fauna that inhabit the fishing grounds where the wedge clam is targeted. For this purpose, three samples were collected every fishing day in each location, from different tows once commercial wedge clams were sorted, comprising discarded organisms and inorganic remains (e.g. bioclasts, gravels). A total of 12 samples (4 fishing days × 3 samples) were collected onboard, labeled and transported to the laboratory, where they were stored at -20 °C until further processing.

Once defrosted, inorganic remains were separated from each sample and quantified, whereas individuals were identified to species level (whenever possible) and quantified (abundance and biomass). The taxonomic identification of individuals followed specialized bibliography on Atlantic and Mediterranean fauna (e.g. Tortonese, 1965; Zariquiey, 1968; Ocaña Martín et al., 2000; Southward and Campbell, 2006; Gofas et al., 2011), as the Alboran Sea represents a point of confluence of three areas (Lusitanian, Mauritanian and Mediterranean) included in the Atlanto-Mediterranean province (Ekman, 1953).

Sediment characterization

For the granulometric analysis, sediment samples (around 100 g) were washed over a 0.063 mm sieve, in order to separate the mud fraction (silt and clay) that was then computed as the difference in dry weight before and after the wash. Subsequently, the sediment was sieved over a column of sieves (2, 1, 0.5, 0.25, 0.125 and 0.063 mm), weighing the fractions retained on each sieve (dry weight). Buchanan grain size classification (Buchanan, 1984) was used to characterize the type of sediment. Granulometric parameters including mean grain size (M_G; median particle size of sediment) and sediment sorting coefficient (σ_G; the lower the sorting numerical value the better the sediment has been sorted) (Trask, 1932) were calculated according to the geometric (modified) Folk and Ward (1957) graphical measures, and were analyzed using the software GRADISTAT, a grain size distribution and statistics package for the analysis of unconsolidated sediments (Blott and Pye, 2001).

Data treatment and statistical analysis

Statistical comparisons among sediment composition (e.g. gravel, sand, mud), faunal components (e.g. abundance, biomass), wedge clam lengths, shell and foot damages, and survival estimates between sites depending on towing speeds were performed using the one-way ANOVA. Analyses to test the normality of data (Kolmogorov-Smirnov) and to verify the homogeneity of variances (Barlett) were executed prior to ANOVA analyses. Whenever ANOVA assumptions were not met, a Kruskal–Wallis test (K-W), the corresponding non-parametric analysis of variance, was performed. The relationships between proportions of damaged wedge clams and (i) sediment content, and (ii) decapod biomass in samples were analyzed using non-parametric correlation (Spearman's rank) analysis. Prior to analyses, all variables expressed in percentages were log (x + 1) transformed. All statistical analyses were conducted using SPSS 15.0 package and PRIMER v6 software (Clarke and Warwick, 2001).

Results

Sediment characteristics

All sampling stations from both sites were composed mostly of sand (98.6 ±0.1% by weight; mean ±SE; n= 12), with minor contents of mud (1.1 ±0.1%) and gravel (0.3 ±0.1%) (Table I). Mean grain size (M_G) showed that most samples were predominantly fine-sand, with some samples collected in Fuengirola corresponding to medium and coarse sand; however, without significant differences in sediment content between samples (ANOVA: $p > 0.05$). Sediment sorting coefficients (σ_G) were very similar and ranged between 1.50 and 1.75, corresponding in all cases except one to moderately well sorted sediments (i.e. similar-sized grains) (Table I).

Pebbles and bioclasts collected with MDs and retained together with the faunal samples in the collecting system were quantified. The mean content of pebbles per sample (expressed as a percentage of total weight) was significantly higher in Caleta (80.1 ±2.7%) than in Fuengirola (27.4 ±5.7%) (K-W: χ^2= 8.3, *p*< 0.05), whereas the content of bioclasts showed the opposite pattern (60.2 ±6.3% in Fuengirola against 27.4 ±1.5% in Caleta) (K-W: χ^2= 8.3, *p*< 0.05).

Target species and discards

The 18 tows performed with MDs in each study site yielded significantly higher catches of commercial wedge clam in Caleta (2293.9 ±287.5 g tow^{-1}) than in Fuengirola (1136.7 ±79.2 g tow^{-1}) (ANOVA: F= 7.9, *p*< 0.05). The size frequency distribution of the two populations showed commercial individuals with maximum lengths of 40.2 mm in Fuengirola and 39.1 mm in Caleta, with significant differences in mean length (K-W: χ^2= 13.6, *p*< 0.005), being larger in Fuengirola (29.8 ±0.1 mm) than in Caleta (29.0 ±0.1 mm). Size frequency distributions displayed slightly different trends, with higher frequencies shifted to larger sizes in the population from Caleta (27-30 mm) compared to that from Fuengirola (25-28 mm) (Figure 2).

The total catch composition from all sampling surveys is illustrated in Figure 3, whereas the mean percentages of commercial and discarded target species, as well as other discarded organisms are summarised in Table II. The commercial fraction of wedge clams represented 77.3 ±3.3% of the total catch and the discarded fraction contributed with 13.2 ±2.4%; other discarded organisms (9.5 ±1.4%) included mostly molluscs, crustaceans (e.g. crabs and hermit-crabs), and echinoderms (e.g. sea-urchins and ophiurids). In both sites, the most abundant discarded species was*D. trunculus* (individuals below the minimum conservation reference size - MCRS), followed by the venus clam *Chamelea gallina* (both commercial-size individuals and those below MCRS), the decapods *Liocarcinus vernalis*, *Portumnus latipes* and those belonging to the superfamily Paguroidea (i.e. hermit-crabs), the echinoid *Echinocardium* cf. *mediterraneum* and the ophiurid *Ophiura ophiura*. Significant spatial differences in the abundances were observed for discarded *D. trunculus* (ANOVA: F= 13.7; *p*< 0.05), *L. vernalis* (K-W: χ^2= 4.3, *p*< 0.05), *P. latipes* (ANOVA: F= 18.9; *p*< 0.05) and *E.* cf. *mediterraneum* (ANOVA: F= 10.4; *p*< 0.05) (Table II).

Damage rates

Of 10839 commercially-size wedge clams analyzed, 259 ind. (2.4%) suffered some type of shell damage, including holed umbos, chipped margins and split or crushed valves (Figure 4). Proportions of shell-damaged individuals per tow were significantly higher in Caleta (3.4%, corresponding to 250 ind.) than in Fuengirola (0.2%, 9 ind.) (K-W: χ^2= 20.7, *p*< 0.005). Increased in tow speed significantly increased the proportion of damaged individuals in Caleta (K-W: χ^2= 6.3, p< 0.05), with highest rates at 0.3 knots tows (7.7 ±3.1%, 122 ind.); contraril, proportions were similar in the different towing speeds in Fuengirola (maxima= 1.6%, 3 ind.) (K-W: p> 0.05), as well as considering fine sand bottoms versus medium sand bottoms (K-W: p> 0.05). On the other hand, a very strong positive correlation was observed between proportions of shell-damaged individuals and pebbles content (%) retained in the collecting system (Spearman: ρ_S= 0.90; p< 0.001) (Figure 5A).

The position of the damage was analyzed in 132 randomly selected individuals (from a total of 259 ind. observed with any type of damage) with lengths ranging between 22.1 and 34.3 mm (mean: 28.8 ±0.2 mm). Most individuals showed light damage (e.g. chipping on the edge; 33.3%, corresponding to 44 ind.) or partly scratched (<50% of the valve surface; 55.3%, 73 ind.) valves (Figure 4A-B), from which 31.6% (23 out of 73 ind.) showed further dislodged valves; whereas 11.4% (15 ind.) had crushed valves (≥50% of the valve surface) (Figure 4C-D). From the former (light damage, partly scratched), right valves were more frequently damaged (35.9%, 42 ind.) than left valves (29.1%, 34 ind.), whereas 35% (41 ind.) had both valves damaged; from the latter (crushed valves), there was a dominance of crushed left valves (66.7%, 10 ind.) over right valves (26.7%, 4 ind.). Regarding the most frequently damaged areas (AD, PD, AV and PV), most shells had damage in the combination AD-AV (58.8% [78 ind.] and 50% [66 ind.] for left and right valves, respectively), followed by AD (26.5% [35 ind.] and 28.6% [38 ind.], respectively) and AV (11.8% [16 ind.] and 9.5% [13 ind.], respectively) (Figure 4E-F). The PD and PV areas were the less damaged in both valves. The 60.9% (81 ind.) of damaged individuals showed shell lengths between 28-31 mm (maximum damage frequency at 29 mm); however, no correlation was found between shell length and damage frequency (Spearman: p> 0.05).

Overall, 15.9% of analyzed individuals (343 out of 2155 ind.) showed some type of foot-damage (Figure 6). A significantly higher proportion of foot-damaged wedge clams per tow were found in Caleta (22% in 1076 ind.) than in Fuengirola (9.8% in 1079 ind.) (ANOVA: F= 21.4, p< 0.001). These differences were mostly due to the type 2-severe damage, which showed significantly higher proportions in Caleta (16.1% [173 ind.] versus 3.6% [39 ind.]) (ANOVA: F= 39.8, p< 0.001), being 29 and 26 mm the most frequent shell lengths with type 2 foot damage in Caleta and Fuengirola, respectively (Figure 2). In individuals with type 1-intermediate damage, proportions were similar among sampling sites (ca. 6% [64 ind. in Caleta, 67 ind. in Fuengirola], respectively). Regarding samples collected in Fuengirola, proportions of foot-damaged individuals did not display significant differences between fine sand and medium sand bottoms (ANOVA: $p> 0.05$, in all cases). Moreover, proportions also did not differ among towing speeds (ANOVA: $p> 0.05$, in both sites).

Individuals with damaged foot displayed a slightly larger shell length (28.7 ±0.2 mm) than those with undamaged foot (28.3 ±0.08 mm) (ANOVA: F= 5.3; $p< 0.05$); however, no correlation was found between shell length and proportion of foot-damaged individuals (Spearman: $p> 0.05$). On the other hand, a moderately strong significant positive correlation occurred between proportions of foot-damaged wedge clams and biomass (expressed as a percentage of total catch) of decapod crustaceans in samples (Spearman: $\rho_S = 0.74$; $p< 0.01$) (Figure 5B).

Survival rates

The proportion of wedge clams that survived after 24 h purification treatment was >99% (Figure 7), without significant spatial differences between Fuengirola and Caleta (K-W: $p> 0.05$). A slightly higher number of dead individuals was observed in faster towing speeds (Figure 7); although survival proportions did not differ significantly between towing-speeds (K-W: $p> 0.05$). After 72 h of cold storage, the mean proportion of surviving individuals was 99.1 ±0.3% (in 3579 ind.) for Fuengirola, and 99.3 ±0.1% (in 7001 ind.) for Caleta (Figure 7), without significant differences related to sampling location (K-W: $p> 0.05$) or towing speed (K-W: $p> 0.05$). Controls (individuals not treated in the purification centre) showed proportions of surviving individuals ranging between 97.0% (in 694 ind.; Fuengirola) and 99.9% (in 751 ind.; Caleta) (K-W: $p> 0.05$). The survival rate of *D. trunculus* at the end of the experiment was very high (99.2%).

Discussion

Habitat characteristics (e.g. percentage of sands, gravels and mud) and depth are major environmental variables influencing the spatial variability of sublittoral macrofaunal benthic communities associated with soft bottoms (Snelgrove & Butman 1994). This would partly explain the higher commercial catches observed in Caleta de Vélez, as hauls were carried out at deeper bottoms (mean depth: 2.5 ±0.2 m) than those carried out in Fuengirola (mean depth: 1.9 ±0.6 m). This would be linked to the depth segregation phenomenon reported for the wedge clam, with larger individuals found at greater depths (Gaspar et al., 1999; Manca Zeichen et al., 2002). A comparison of the results obtained here with those reported by Urra et al. (2017) for the same area shows that (1) discards are characterized by the same faunal groups and dominant species, and (2) undersized target individuals of the wedge clam represent the highest discarded biomass and abundance in both cases, as it corresponds to one of the dominant species of this facies of the well sorted fine sand community. The proportion of wedge clam undersized individuals has been always higher than 30 % of the discarded fraction in this artisanal fishery, reaching values up to 65 %, which promotes the maintenance of the populations of this commercial species in these fishing grounds. It is remarkable the higher proportion values observed in autumn 2018 (48-65 %) than in autumn 2013 (31-37 %) in both areas, which would reflect a high temporal and spatial variability in recruitment patterns. Moreover, some authors have documented favourable environmental windows for recruitment of bivalves (e.g. Lagarde et al., 2017), especially linked to the availability of phytoplankton biomass, which may affect the breeding stocks of suspensivorous bivalves in shellfish basins (Dame, 2011). In this line, the northern Alboran basin is characterized by the occurrence of enriched nutrient upwellings (Sarhan et al. 2000), which could benefit the recruitment of this and other commercial bivalves, as well as of other species, especially those years when the intensity of the upwelling is more prominent.

Shell damage

The grain size distribution of bottom sediments, mainly its greater or lesser content of hard particles, represent a factor to be considered in relation to the potential damage that any benthic resource can suffer. In this line, significantly higher proportions and a positive correlation of wedge clams with damaged shells (i.e. dislodged or fragmented valves) were observed in the fishing ground with higher content of pebbles. MDs are towed scraping the seabed and anything collected by the dredge larger than the mesh size is retained inside the mesh bag. This includes target (e.g. wedge clams) and non-target species, gravels, small rocks and boulders, bioclasts (e.g. empty shells), debris or any other object in the dredge path. As the collecting system remains closed or partly clogged due to the catch, the hard material promotes the abrasion between organisms with weak exoskeletons and those with hard shells and with debris, damaging the catch during towing and hauling (Pranovi et al., 2001; Broadhurst et al., 2006).

In this context, species-specific characteristics (e.g. morphology, body size, structure) make organisms more or less susceptible to damage (Hall-Spencer et al., 1999; Bergmann et al., 2001; Leitão et al., 2009; Urra et al., 2019); moreover, the extent of this damage is influenced by fishing gear and tow characteristics (Gaspar and Chícharo, 2007 and references therein), and even seasonality. In this particular, Urra et al. (2017) observed a significant higher damage level on *D. trunculus* in cold months , which was linked to a combination of factors including higher sediment movements caused by stronger currents and storms in autumn and winter, as well as to the species biology (e.g. molt in decapods, lack of biomineralization during certain periods) that makes them more susceptible to damage by fishing activities, their behavior (e.g. bathymetric migrations linked to reproductive strategies) or to the fishing operation (e.g. higher probability of recapturing damaged individuals) (Kaiser, 1996; Bergmann et al., 2001; Raviv et al., 2008). Considering all this, slow moving/sessile and soft-bodied benthic organisms, as well as those with vulnerable exoskeletons, relatively thin shells or fragile morphology with arms and appendages easy to lose, are especially vulnerable to dredges and usually show the highest damage rates, whereas resistant taxa (e.g. thick shelled) show a lower proportion of mechanical damage (Kaiser, 1996; Hall-Spencer et al., 1999; Bergmann and Moore, 2001a, b; Pranovi et al., 2001; Anjos et al., 2018). Regarding faunal groups and discards analyzed in the mechanical dredging targeting wedge clam in the northern Alboran Sea, Urra et al. (2017) reported that gastropods and hermit crabs were the most resistant taxa due to the protection provided by shells, which promotes their survival once they are returned to the sea. On the other hand, echinoderms such as ophiuroids and asteroids and decapods showed the highest proportions of damage due to their fragile morphology. Chronic and intensive bottom dredging and trawling can potentially lead to clear changes in benthic community composition, promoting the dominance of carnivores and opportunistic scavengers of moribund discarded benthic fauna, as well as alterations to the sea-bottom morphology (Collie et al., 2000; Thrush and Dayton, 2002; Hinz et al., 2009; Pusceddu et al., 2014). Further experimental hauls with modified mechanical dredges on different soft bottom types should be undertaken in order to investigate how to minimize their ecological impact.

The wedge clam seems to have a resistant shell to dredging operations, being unlikely to crack and break easily during towing, as it is reflected by the low proportion (2.4%) of shell-damaged individuals collected in this study. Abrasion and compaction have been identified as important drivers inducing shell fragmentation (Zuschin et al., 2003 and references therein). The magnitude of abrasion is controlled by grain size and sediment sorting, being greater in fine and coarse than in medium sand, whereas shell fragmentation induced by compaction is controlled by mechanical shell strength and by extrinsic factors, including sediment grain size and burial orientation. Regarding this, the higher proportions of shell-damaged wedge clams observed in Caleta de Vélez could be linked to the higher amount of larger gravels (i.e. pebbles, cobbles) retained in the collecting system while towing; moreover, a positive correlation was observed between these two parameters. Impacts and interactions with pebbles, rocks and bioclasts during dredge towing, which represent a dynamic stress affecting shell strength (Pranovi et al., 2001; Zuschin et al., 2003; Broadhurst et al., 2006), may macerate the catch, promoting shell fragmentation. In this context, shell resistance to breakage depends on a broad range of features, including size (length, width, height, volume) and especially thickness, as well as shape, microstructure and sculptural features (Currey, 1988; Kohn, 1999; Zuschin et al., 2003). In this line, Vasconcelos et al. (2011) reported that in the commercially exploited smooth clam (*Callista chione*), the most effective predictors of shell strength were thickness (in compression experiments) and width (in compaction experiments), suggesting that thicker shells are stronger, heavier and more difficult to dislodge and break, which could also be the case of *D. trunculus*.

On the other hand, the most frequently damaged areas in wedge clams´ shell (both left and right valves) were the anterior dorsal (AD) and ventral (AV) areas, both separately and in combination. These results show that, although compaction forces may spread and dissipate over the entire shell surface, apparently the most vulnerable area of the shell to suffer fragmentation is along the anterior edge. This breakage pattern provides valuable information about susceptible parts and specific breakage mechanisms of this important commercial species. Further experimental studies are required to understand the response of *D. trunculus*, as well as of other commercial bivalve species, to potential shell damage during mechanical dredging, as this data is scarce (Moschino et al., 2003; Vasconcelos et al., 2011), in order to provide suitable information to improve the design of bivalve dredges and decrease the impact of towing fishing gears on macrobenthic organisms. This is for target species, but also for non-commercial taxa, because it promotes the survival of discarded individuals, contributing to the sustainable exploitation of the resource.

Another factor to be considered regarding the magnitude of shell damage is towing speed. In our case, a higher number of damaged individuals was observed in hauls performed at 0.3 and 0.5 knots than in those at 0.1 knots; moreover, after the purification treatment (24 h) and storage in the refrigerator (72 h), a higher number of intact and apparently healthy wedge clams were found dead in samples collected at higher speeds. In fact, many authors reported that, despite an apparent good condition, long-term mortality of discards is likely to occur due to sub-lethal damage, internal injuries and physiological stress (Kaiser and Spencer, 1995; Gaspar and Monteiro, 1999; Bergmann and Moore, 2001b; Pranovi et al., 2001). Towing speed has been identified by several authors as a key technical factor that can have negative effects on most organisms health, and thereby on mortality (Suuronen, 2005; Broadhurst et al., 2006; Gaspar and Chícharo, 2007), although very little direct scientific evidence exists. According to Broadhurst et al. (2006), higher towing speed, among other factors, probably increases the mortality of caught organisms by promoting more collisions with different sections of the fishing gear. Furthermore, a higher towing speed together with the weight of the catch make the mesh of the collecting system to close or the metallic grid to clog during the tow, preventing the escape of individuals and therefore increasing their damage probability (Gaspar and Chícharo, 2007). A simple operational change in the fishing technique, such as lowering the towing speed, may result in lower damage and mortality rates, similar to the observed for towing duration in the case of razor clams *Ensis siliqua* (Linnaeus, 1758) (Gaspar et al., 1998).

Foot damage

A wide variety of types of foot damage was observed in live individuals collected in both study areas, ranging from small cuts in the margin to total loss of the foot together with damage on gonads and hepatopancreas. Some co-marginal cuts at the edge of the foot could be due to amputation caused by a rapid and powerful closure of the valves stress-induced by capture, as injuries were compatible with this closure. Deep cuts, sometimes perpendicular to the margin of the foot, are probably related to the mechanical action of predators. Despite this, shells of foot-damaged wedge clams were in good condition and usually did not show any sign of breakage. On the other hand, no significant relationship was found between frequency of foot damage and shell length of individuals. Moreover, proportions of foot-damaged clams did not show any significant difference between towing speeds or locations (i.e. different pebbles content); however, a significantly higher proportion of individuals with damaged foot was observed in Caleta than in Fuengirola.

Information on predation on bivalves is scarce and most studies are focused on cropping or nipping of siphons, such as that by Trevallion (1971), who analyzed the loss of *Tellina*´s siphons by flatfishes in northwestern Scotland; Coen and Heck (1991), who studied damaged siphons in *Mercenaria mercenaria* (Linnaeus, 1758) in eastern United States; and Ansell et al. (1999), who documented damages to the siphons in *Donax vittatus* on the Scottish East coast. In the only work that has specifically addressed foot damage on *Donax* spp. populations, Salas et al. (2001) reported that *D. trunculus* was the most affected species in southern Spain, with ca. 18% of the individuals with foot damaged over the year, similar to the ca. 16% reported here. These authors documented that almost all size classes were affected, except the smallest ones, relating this damage to predators. The main predators caught with the clams in the study by Salas et al. (2001) were the decapod crustaceans *Liocarcinus vernalis* and *Portumnus latipes*, the same species sampled in the present study, together with other potential predator decapods, including *Atelecyclus undecimdentatus*. The former two species were the more active foot predators in aquarium observations, apparently attacking whatever prey size is available above a particular threshold, probably according to their own sizes (Salas et al., 2001). Moreover, Blundon and Kennedy (1982) proposed that a crab diet, with regard to infaunal bivalves, is a function of prey availability, among other factors, and in the present case presented, the target species *D. trunculus* represents one of the most common macrobenthic organisms on bottoms where this fishery takes place. Furthermore, Salas et al. (2001) reported the ability of *L. vernalis* and *P. latipes* to snap or nip the foot of wedge clams without visibly damaging the shell, which coincides with the low breakage signals of the damaged-foot individuals observed in this study. These observations would relate the significantly higher percentage of foot-damaged individuals observed in Caleta (22% versus 9.8%) with the higher proportion of decapods found in samples from this location (19% of the total biomass versus 6%). Therefore, foot damage on wedge clams would be positively correlated with the frequency of potential foot-nipping predators on the bottoms where this target species is caught.

On the other hand, in the present experiments, this foot predation does not seem to have any effect on the survival of wedge clams, as foot-damaged individuals were alive after every treatment, including those with a great part of the foot damaged or nipped, similarly to observations made by Salas et al. (2001). Therefore, foot predation on *D. trunculus* would be understood as a sublethal damage, as wedge clams with partial or total foot loss will have more difficulty burying in the surf zone where they inhabit, being more prone to predation.

Survival rates

Depuration is a legal requirement in European countries for marketing fresh molluscs in order to protect consumers' health. The scarcity of areas that are to any type of contamination makes this treatment mandatory for live bivalves for human consumption collected in Class B areas according to the EU Regulation No 854/2004, as pathogenic bacteria, viruses, toxins and chemical pollutants accumulated in their tissues via water filtration can pose a risk to public health (Bellou et al., 2013; Fernández et al., 2016). The present results showed survival rates of 98.8-100% after the 24 h purification treatment, regardless of the different bottom types and towing-speeds. Information regarding the effects of purification treatment on the survival of commercial bivalves is lacking, as literature on shellfish depuration is mostly focused on microbial and contaminants elimination (Richards, 1988; McLeod et al., 2017; Martinez-Albores et al., 2020). Nevertheless despite the limited number of samples collected in both locations, the present experiments showed that the 24 h purification does not significantly affect the survival of wedge clams. If the transport of commercially-sized wedge clams to the purification centre (i.e. shortest possible duration, well stabilized and under cool temperature) and the treatment are adequate, 99.9% of clams leaving the purification centre are expected to arrive alive at the seafood market.

Once marketable wedge clams have left the purification centre, they are usually put into plastic mesh bags and kept cold in refrigerators until being sold in the fishing market. In our case, treated wedge clams were stored inside mesh bags at 4 °C for 72 h, and the survival rates ranged between 94-100%, with very few dead individuals observed after 48 h and 72 h of cold storage. Furthermore, control samples with wedge clams that were not treated at the purification centre and just kept refrigerated after its capture, showed between 92-100% of living individuals after 96 h. In this line, *D. trunculus* inhabits high-energy environments with daily salinity changes and large temperature fluctuations, thus developed a natural resistance that allows supporting long exposure times (Gaspar and Monteiro, 1998). This experience shows that 72 h refrigeration at the usual preservation temperature for shellfish does not cause severe mortality of previously purified commercial wedge clams, with survival estimates always over 90%. As long as the cold chain is maintained and the storage conditions are adequate, wedge clams remain in good conditions for human consumption during four days after their capture.

Final remarks

Based on the present results, and taking into account the limited number of samples, it would be desirable to repeat these experiences with a larger number of fishing vessels to confirm the observed patterns. In this way, recommendations could be made regarding the optimal towing speed in an attempt to minimize the damage on the benthic communities where bivalve mechanical dredging takes place. This would be especially desirable in areas widely recognized as hot-spots of marine biodiversity and where locally important artisanal fishing activities are performed, such as the Alboran Sea.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Figure Legends

Figure 1. Map with the location of the study area, in the northern margin of the Alboran Sea. Sampling stations (small black dots) were selected in the vicinities of two of the main fishing ports of southeastern Spain: Fuengirola and Caleta de Vélez.

Figure 2. Size frequency distribution of wedge clams collected in southern Spain (A), with detail of the different types of damage observed in Fuengirola (B) and Caleta de Vélez (C).

Figure 3. (A) Composition of samples (commercial wedge clams *Donax trunculus* and discarded organisms), expressed as percentage biomass of total catch per tow, in samples collected using mechanical dredges in Fuengirola (FNG) and in Caleta de Vélez (CV) (northern Alboran Sea). Composition of the discarded fraction, including undersized wedge clams, in relation to site and based on biomass (B) and abundance (C).

Figure 4. Commercial wedge clams (shell length ≥ 25 mm) with different damage degree: (A) shell with both valves scratched on the anterior dorsal (AD) area; (B) shell with crushed AD and posterior dorsal (PD) area of the left valve; (C) shell with crushed AD, anterior ventral (AV) and posterior ventral (PV) area of the left valve; (D) crushed shell and dislodged valves. Frequency distribution of damaged areas detected in *D. trunculus* shells (right-E and left-F valves) during bivalve mechanical dredging.

Figure 5. Spearman correlations established between (A) proportion of shell-damaged wedge clams *Donax trunculus* and content of pebbles in samples (expressed as a percentage of total weight retained in the collecting system); and between (B) proportion of foot-damaged wedge clams and proportion of decapod crustaceans in samples. Data were log (x+1) transformed.

Figure 6. Commercial wedge clams with undamaged foot (A). Wedge clams with type 1-intermediate damage included small cuts in the dorsal (B), ventral (C) and anterior margin (D), as well as co-marginal cuts along the ventral margin probably related to the closure of the shell (E-F, same individual). Wedge clams with type 2-severe damage included partial (G) or total (H) loss of the foot.

Figure 7. Mean survival curves for wedge clams *Donax trunculus* collected in Caleta de Vélez (A) and in Fuengirola (B) after 96 hours of treatment.

Table Legends

Table I. Location and sedimentary characteristics of each sampling station. Mean grain size (M_G), according to sizes: <0.063 mm silt or mud, 0.063-0.125 mm very fine sand, 0.125-0.25 mm fine sand, 0.25-0.5 mm medium sand, 0.5-1 mm coarse sand, 1-2 mm very coarse sand, >2 mm gravel. Sediment sorting coefficient (σ_G) according to: σ_G <1.27 very well sorted, 1.27< σ_G <1.41 well sorted, 1.41< σ_G <1.62 moderately well sorted, 1.62< σ_G <2.00 moderately sorted; 2.00< σ_G <4.00 poorly sorted, 4.00< σ_G <16.00 very poorly sorted, σ_G >16.00 extremely poorly sorted. FNG, Fuengirola; CAL, Caleta de Vélez. MWS, moderately well sorted; MS, moderately sorted.

Table II. Total weight (g) and mean biomass (expressed as a percentage of total catch) of commercial and discarded wedge clams *Donax trunculus*, as well as other discarded organisms, in samples collected in Fuengirola and in Caleta de Vélez (northern Alboran Sea).